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INVESTIGATING METAL-CUTTING PROCESSES: III. INTERPRETATION OF THE CUTTING PROCESS AS A PLASTIC COMPRESSION PROCESS

Docent M. Klushin

A series of articles under the general title "Physical Fundamentals of Metal Cutting" appeared in the magazine Tekhnicheskaya Fizika for 1940-41. Those articles were written by Professor V. D. Kuznetsov, of Tomsk State University, laureate of the Stalin Prize and Corresponding Member of the Academy of Sciences USSR.

In 1944 in the book Fizika Tverdogo Tela (Physics of Solids), Volume III Materialy po Fizike Rezaniya Metallov (Materials on Physics of Metal Cutting), V. D. Kuznetsov repeated the basic conclusions, presented in the above-mentioned articles, and introduced certain new considerations.

Kuznetsov is the first physicist to initiate a systematic study of the metal-cutting process. The basic idea of his theory is an interpretation of the cutting process as a successive compression of chip portions attached before shearing to the metal being machined.

Representing the cutting process as a process of plastic compression, Kuznetsov outlines methods for theoretically calculating the values of cutting forces, substantiating those methods by investigations of plastic compression of metals, conducted under his supervision by a group of his collaborators and students.

M. A. Bol'shanina developed a general equation of plastic flow, which under the condition of constancy in deformation rate has a form:

$$\sigma = \sigma_o \left(\frac{\ell_o}{\ell}\right)^n \quad \text{or} \qquad (60)$$

$$\sigma \cdot \ell^n = \sigma_o \cdot \ell_o^n , \qquad (61)$$

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where l_0 is the initial length of a deformed body, σ_0 is the arbitrary yield strength, l is the length of the deformed body under action of the load P, and σ is stresses formed in the body under action of the load P. On compressing the cylindrical or parallelepiped specimen, the initial height h_0 should be introduced instead of l_0, and l has to be replaced by the specimen height h, corresponding to a certain compressing force P. Then the case of plastic compression may be:

$$\sigma = \sigma_0 \left(\frac{h_0}{h}\right)^n \tag{62}$$

and

$$\sigma h^n = \sigma h_0^n . \tag{63}$$

Equation (63) looks like the equation of polytropic compression of a gas and therefore is defined as the equation of the polytropic curve of plastic compression.

Expressing stresses by the acting force and area of the specimen cross section, we obtain:

$$\frac{P \cdot h^n}{S} = \frac{P_0 h_0^n}{S_0} , \tag{64}$$

but, under the condition of constancy in the volume of the specimen being deformed:

$$S \cdot h = S_0 h_0 = const \quad or$$

$$\frac{S}{S_0} = \frac{h_0}{h}$$

Then equation (64) may be written in the form:

$$P \cdot h^n = P_0 \cdot h^n \frac{S}{S_0} = P_0 \cdot h_0^n \frac{h_0}{h} \qquad \text{or}$$

$$P \cdot h^{n+1} = P_0 \cdot h_0^{n+1}$$

Designating: $n + 1 = m$, we obtain (65)

$$P \cdot h^m = P_0 \cdot h_0^m = const \tag{66}$$

Equation (66) may be written in the form: $\lg P = -m \cdot \lg h + \lg C$. (67) The latter form of the equation shows that the relation between the gradually increased compressing force P and the height h of the compressed specimen in logarithmic coordinates is represented by a straight line.

Application of the equation of the compression polytropic curve to establishing regularities of the cutting process is given by Kuznetsov in two variations. The first variation is based on investigations conducted by K. A. Zvorykin, who arrived at the conclusion that in free cutting the cutting force P_z may be expressed by the empirical formula:

$$P_z \quad K' \cdot b \cdot a^{\xi} . \tag{68}$$

If σ denotes the cutting coefficient, which, according to Kuznetsov, may be defined as a conventional stress, then

$$\sigma = \frac{P}{a \cdot b} = \frac{K' \cdot b \cdot a^{\xi}}{a \cdot b} = K' a^{\xi - 1} \tag{69}$$

if h denotes the length of the chip element, then it follows from the illustration:

$$h = \frac{a}{\sin \beta_1} \tag{70}$$

where the angle $\beta_1 =$ const at given cutting angle δ and at all values of cut thickness (see Figure 1):

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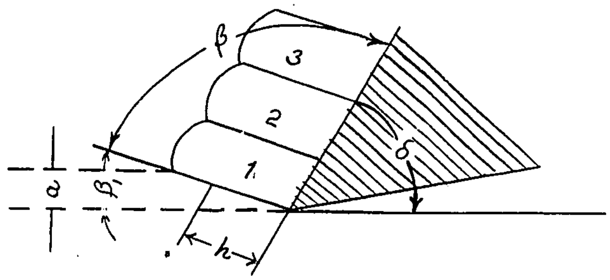

Figure 1

After introducing the expression for h into the formula (69) we obtain:

$$\sigma \cdot h^{1-\xi} \cdot (\sin\beta_1)^{1-\xi} = K \quad \text{or}$$

$$\sigma \cdot h^{1-\xi} = const \tag{71}$$

Considering the free cutting of metals as a process of successive plastic compression, it is possible to assume that equations (63) and (71) express the same phenomenon of compression and consequently:

$$\sigma \cdot h^{1-\xi} = \sigma \cdot h^{n} = \sigma \cdot h^{m-1} \tag{72}$$

which is possible only under the condition:

$$1-\xi = m-1 \quad \text{or}$$

$$\xi + m = 2. \tag{73}$$

Another variation, developed in 1944, contains different ideas.

During the cutting process, the layer of metal to be cut off is compressed by pressure of the cutting tool. The concepts of initial height h_o and current height h in this case become indefinite, and therefore it is more convenient to present the equation of the polytropic curve (63) in coordinates: stress σ and relative deformation of compression.

$$\epsilon = \frac{h_o - h}{h} \tag{74}$$

Substituting into equation (63) the expression for $\frac{h_o}{h}$ from (74), we obtain:

$$\sigma (1-\epsilon)^{h} = \sigma_o = const. \tag{75}$$

By introducing the relative increase of the cross section

$$\psi = \frac{S - S_o}{S_o} \tag{76}$$

the equation of the polytropic curve may be expressed as follows:

$$\frac{\sigma}{(1+\psi)^{n}} = \sigma_o = const \tag{77}$$

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The deformation of the layer being cut off in the cutting process is characterized by the contraction of the chip.

Let us define the coefficient of chip contraction as a ratio of the tool path ℓ and chip length ℓ_1.

$$\xi_\ell = \frac{\ell}{\ell_1} \tag{78}$$

then the relative longitudinal contraction ϵ_ℓ will be:

$$\epsilon_\ell = \frac{\ell - \ell_1}{\ell} \tag{79}$$

The transverse contraction ξ_q may be defined as a ratio between the cross section area S of a chip and the area S_0 of a cut:

$$\xi_q = \frac{S}{S_o} \tag{80}$$

then the relative transverse contraction ϵ_q will be:

$$\epsilon_q = \frac{S - S_o}{S_o} \tag{81}$$

Since the volume V_o of a cut is equal to the volume V of the removed chip, it is possible to write: $\ell_o \cdot S_o = \ell \cdot S$ from which

$$\frac{\ell_o}{\ell} = \frac{S}{S_o}$$

i.e., the longitudinal contraction is equal to the transverse contraction:

$$\xi_\ell = \xi_q \tag{82}$$

Substituting in equation (77) the relative increase ψ of the cross section by the value of the relative transverse contraction ϵ_q we may write:

$$\frac{\sigma}{(1+\epsilon_q)^n} = \sigma_o = const \quad or$$
$$\sigma = \sigma_o (1+\epsilon_q)^n. \tag{83}$$

Under steady conditions of cutting the cutting force P_Z = const, i.e.,

$$P_z = \sigma \cdot S = \sigma_o \cdot S_o (1+\epsilon_q)^{n+1} = const$$

because, according to (81),

$$S = S_o (1 + \epsilon_q).$$

But $n + 1 = m$, therefore:

$$P_z = \sigma \cdot S = \sigma_o \cdot S_o (1+\epsilon_q)^m = \text{const or}$$

$$\sigma \cdot S = \sigma_o \cdot S_o \xi_q^m = \sigma_o \cdot S_o \cdot \xi_\ell^m = \text{const since}$$

$$1 + \epsilon_q = \xi_q = \xi_\ell.$$

Thus, for the cutting force we obtain:

$$P_z = \sigma_o \cdot S_o (1 + \epsilon_q)^m \tag{84}$$
$$P_z = \sigma_o \cdot S_o \cdot \xi_\ell^m.$$

(85)

Very essential is the factor that the formula (85) contains only those values which have real physical significance, namely: σ, being the conventional yield strength, may be determined experimentally from compression of cylinders or parallelepipeds; S_0 is the cross-section area of the cut determined by the values of feed s and cutting depth t; ξ_ℓ is the longitudinal contraction of the chip; m, the index of the compression polytropic curve, may be determined from experiments for compression.

In connection with all this, equation (85) may be considered as a theoretical relationship.

Further, Kuznetsov utilizes equation (85) for deduction of the following relationship: It is established that the contraction of a chip does not depend on the width of a cut, but decreases with increase in the thickness of a cut. This factor may be expressed by the empirical formula:

$$\xi_\ell = \frac{C_1}{a^{y_1}} \tag{86}$$

where C_1 and y_1 are certain constants.

Substituting into equation (85) from (86), we obtain:

$$P_z = C_1^{\,m} \cdot \sigma \cdot \frac{a \cdot b}{a^{my_1}} \quad \text{or}$$
$$P_z = C_2 \cdot b \cdot a^{1-my_1}, \tag{87}$$

since the exponent of the chip thickness a is usually smaller than unity because m and y_1 are positive values.

Comparing (87) and (68) we obtain:

$$\xi = 1 - my_1 \tag{88}$$

But according to (73) $\xi + m = 2$. Consequently $y_1 = 1 - \frac{1}{m}$. (89)

The idea of taking into consideration the contraction of a chip in the deduction of the formula for the cutting force P_z and expression of dependence of the contraction on the cutting depth in the form of an exponential function belong to Professor V. A. Krivoukhov, who also developed the equation for calculating the maximum stress of plastic compression in the layer being cut off under the condition of restricted cutting (V. A. Krivoukhov, "Deformation of Surface Layers of Metal in the Cutting Process," Mashgiz, 1945). Kuznetsov suggests three possibilities for utilization of formulas (73) and (88).

1. Let us assume that experiments were conducted for plastic compression of cylinders, made of material under investigation, and the index m of the compression polytropic curve was determined.

It is possible to calculate the index $\xi = 2 - m$ and the index $y_1 = \frac{m-1}{m}$ without performing the cutting operation.

2. Let us assume that the index y_1 is determined from cutting experiments and studying the chip contraction. Then, without experimental plastic compression, m may be calculated by the formula: $m = \frac{1}{1-y_1}$ and ξ may be determined from the formula: $\xi = \frac{1-2y_1}{1-y_1}$.

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3. If the index ϵ is found from experiments for cutting forces, then it is possible to determine: $m = 2 - \epsilon$ and $y_1 = \frac{1-\epsilon}{2-\epsilon}$.

For experimental confirmation of formula (73) Kuznetsov presents some data.

For instance, Kuznetsov and Vorob'yeva in their joint work obtained for tin:

$$\epsilon = 0.76 \text{ and } m = 1.24, \text{ i.e.,}$$
$$\epsilon + m = 0.76 + 1.24 = 2.00.$$

For lead, according to experiments by Bol'shanina, $m = 0.96$ and $\epsilon = 1.07$ Hence, $\epsilon + m = 1.07 + 0.96 = 2.03$.

For iron, according to experiments by Kunin, $m = 12.5$ and, by various investigations, $\epsilon = 0.75$. Consequently, $\epsilon + m = 0.75 + 1.25 = 2.00$. For aluminum, from experiments by Studenok, $m = 1.09$ and $\epsilon = 0.903$, i.e.,

$$\epsilon + m = 1.993 \approx 2.00$$

In addition, Kuznetsov also gives some experimental results for confirming (88). Thus in the machining of tin, when the cutting angle $\delta = 45°$, it was found that $\xi_\ell = 1.34$ at $a = 10$ mm, and $\xi_\ell = 1.31$ at $a = 4$ mm. Obviously, in given case $y_1 = 0.163$.

For the same specimen $m = 1.24$ and $\epsilon = 0.76$; calculation of ϵ from formula (88) gives $\epsilon = 1-1.24 \cdot 0.163 = 0.77$.

In the machining of copper, when the cutting angle $\delta = 55°$, y_1 was obtained equal to 0.151. The value of $m = 1.30$; consequently, $\epsilon = 1-1.30 \cdot 0.151 = 0.80$. Direct experiments gave $\epsilon = 0.78$.

Thus, it seems, both equations, (73) and (88), are in good agreement with experiments.

However, there are some doubts, caused by the following:

In the deduction of equation (73) Kuznetsov assumes that, with variation of the cut thickness a, the shear angle β_1 remains constant, and, consequently, the chip contraction also remains constant.

But, in the development of formula (88), he supposes that the chip contraction decreases as the cut thickness increases, according to the exponential relationship (86).

Formula (89) was obtained as a result of comparing equations (73) and (88) based on different assumptions. This discrepancy, obviously, will be eliminated during the further development of the theory.

Investigation of the cutting process as a process of plastic compression, conducted by V. D. Kuznetsov and V. A. Krivoukhov, leads to the creation of a new school in the science of metal cutting.

Earlier investigators, such as I. A. Time, K. A. Zvorykin, A. Briks, and Ya. G. Usachev, interpret the process of cutting as a process of successive shears which takes place in the metal layer to be removed. It is admitted that compression of the layer portion adjacent to the front side of the cutting tool, always precedes or follows the shearing phenomenon. However, it was assumed that basic regularities of the cutting process are determined by the magnitude and direction of shears, and the resistance of the metals to cutting is mainly dependent on their shear strength. Consequently, the calculation of cutting forces must be based on those constants which determine the ability of metals to withstand shear stresses.

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Kuznetsov interprets the cutting process as plastic compression. Although he admits that compression, actually causing the chip-forming process, results in partial shearing of the metal layer to be cut off, he thinks that the basic regularities of the metal-cutting process, in particular the chip contraction, are determined by the process of plastic compression and the resistance of metals to cutting is measured by their ability to resist plastic compression. In connection with this opinion, formulas for cutting forces must contain the constants which determine the ability of metal to withstand compressing stresses.

At present, experimental data are not sufficiently numerous for a final decision on the question as to which of these two viewpoints is the more exact in expressing the real nature of the cutting process.

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